



Scaling the Raman Gain Coefficient of Optical Fibers

Rottwitt, Karsten; Bromage, J; Leng, L

Published in:
28th European Conference on Optical Communication, 2002. ECOC 2002.

Publication date:
2002

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Rottwitt, K., Bromage, J., & Leng, L. (2002). Scaling the Raman Gain Coefficient of Optical Fibers. In *28th European Conference on Optical Communication, 2002. ECOC 2002.* (Vol. 3, pp. 1-2). IEEE.

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

SCALING THE RAMAN GAIN COEFFICIENT OF OPTICAL FIBERS

Karsten Rottwitt (1), Jake Bromage (2) and Lufeng Leng (2)

1: OFS Fitel Denmark, present address Research Center COM, Technical Univ. of Denmark, Building. 345v, 2800 Lyngby, Denmark, e-mail: kar@com.dtu.dk

2: Systems Testing, OFS Laboratories, 791 Holmdel-Keyport Road, Holmdel, NJ, 07733, USA

Abstract Scaling rules for the Raman gain coefficient are provided with emphasis on the effective area and wavelength dependence. Translation from measurements made at one pump wavelength to other pump wavelengths is demonstrated.

Introduction

The Raman gain coefficient of an optical fiber is a critical parameter when designing Raman amplifiers as it determines the magnitude and spectral shape of the gain for a given pump wavelength and power. It is convenient to be able to predict the Raman gain coefficient for arbitrary pump wavelengths for different types of fibers or apply measurements made at one pump wavelength to other pump wavelengths. Often the Raman gain coefficient is assumed to scale inversely both with the pump wavelength and the effective area of the fiber at the signal wavelength [1].

In this work, we discuss these assumptions and present results that show the correct scaling, derived from a classical model for Raman scattering. We then test these predictions using measurements of Raman gain spectra for several pump wavelengths.

Raman gain coefficient

The optical properties, such as the refractive index and the Raman gain coefficient, of a light-guiding fiber depend on the constituents of the fiber. Most common fibers consist of a silica, SiO_2 , host to which germania, GeO_2 , is added in the core to increase the refractive index.

The Raman effect originates from interactions between optical phonons and the propagating electric field. The phonons can be imagined as oscillations of the oxygen atom in a Si-O-Si , Si-O-Ge , or Ge-O-Ge bridge. The induced polarization of the molecule can be expanded in terms of the displacement of the oscillator. In this expansion, the permanent polarizability is responsible for Rayleigh scattering, whereas the differential polarizability is responsible for Raman scattering [2].

The force that drives the oscillator originates from the electric energy stored in the material. Thus by applying a conventional model for a harmonic oscillator, the amplitude of the oscillations can be expressed through the induced polarization and the electric field [3].

Combining the induced nonlinear polarization with the amplitude of the oscillations, one may derive the wave equation for light propagating in a dielectric

material starting from Maxwell's equations. By solving this wave equation, the gain coefficient due to stimulated Raman scattering is found to be

$$g_r(\omega_s, \omega_p) = \frac{3\omega_s}{c^2 \epsilon_0 n_s n_p} \frac{\int_A |R_s|^2 |R_p|^2 \text{Im}[\chi^{(3)}] dA}{\int_A |R_s|^2 dA \int_A |R_p|^2 dA} \quad (1)$$

where the subscripts s and p refer to the signal and pump, ω_s is the angular frequency, n_i the effective refractive index, $R_i(r, \omega)$ the transverse part of the electric field, c the velocity of light, and the integrals are over the cross-sectional area of the fiber, A . Due to space limitations, the complete derivation will be shown elsewhere. Equation (1) shows theoretically how the Raman gain coefficient scales with material properties, wavelength, and modal overlap between pump and signal.

Dependence on fiber-composition

Equation (1) also shows how the radial dependence of $\chi^{(3)}$ is taken into account when predicting the Raman gain coefficient. In Ref. [4] we treated this by decomposing $\chi^{(3)}$ into a sum of contributions from Si-O-Si and Si-O-Ge . For realistic germania concentrations, Ge-O-Ge bridges are rare. The relative distribution of Si-O-Si and Si-O-Ge bridges is $(1-2x):2x$, where x is the GeO_2 concentration, which can be obtained from the refractive index profile using Sellmeier data. In Ref. [4] we showed that this decomposition can be used to predict the Raman gain coefficients of germanosilicate fibers. We verified this experimentally for fibers with a broad range of peak Raman coefficients, ranging from 0.35 to 6.0 $(\text{W km})^{-1}$.

Dependence on wavelength and effective area

In some cases the refractive index profile may not be available but the spectrum of the Raman gain coefficient of a specific fiber type may be known from a single measurement at a specific pump wavelength. The task is then to scale the spectrum of the Raman gain coefficient to another pump-wavelength.

If the third-order susceptibility, $\chi^{(3)}$ is assumed to be constant over the entire fiber cross-section, Eq. (1) reduces to

$$g_r(\omega_s, \omega_p) = \frac{3\omega_s \text{Im}[\chi^{(3)}]}{c^2 \epsilon_0 n_s n_p} \frac{1}{A_{\text{eff}}^{ps}(\omega_p, \omega_s)}, \quad (2)$$

where A_{eff}^{ps} accounts for the radial overlap between pump and signal light,

$$A_{\text{eff}}^{ps}(\omega_s, \omega_p) = \frac{\int_A |R_s|^2 dA \int_A |R_p|^2 dA}{\int_A |R_s|^2 |R_p|^2 dA}, \quad (3)$$

The conventional effective area, $A_{\text{eff}}(\omega)$ is given by Eq. (3) with $\omega_s = \omega_p = \omega$, [1]. Using the scaling shown in Eq. (2), the gain coefficient for new pump and signal frequencies (Ω_p, Ω_s) is:

$$g_r(\Omega_s, \Omega_p) = g_r(\omega_s, \omega_p) \frac{\Omega_s}{\omega_s} \frac{A_{\text{eff}}^{ps}(\omega_s, \omega_p)}{A_{\text{eff}}^{ps}(\Omega_s, \Omega_p)} \quad (4)$$

For relevant optical frequencies, $\Omega_s/\omega_s \sim \Omega_p/\omega_p$ and thus, for convenience, the ratio of pump frequencies is used rather than signal frequencies. To verify this scaling, we performed the following experiment. First, we measured the Raman gain coefficient of a non-zero dispersion shifted fiber (with a $55\text{-}\mu\text{m}^2$ effective area at 1550 nm) for four pump wavelengths: 1423.6 nm, 1443.8 nm, 1471.3 nm and 1496.0 nm. These measurements are shown in Fig. (1).

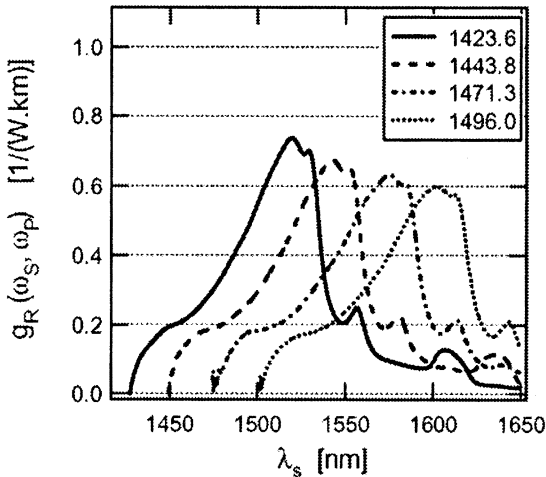


Fig. 1: Measurements of Raman gain coefficient for four pump wavelengths.

If we assume that the transverse part of the electric field is Gaussian, the effective area representing the overlap between pump and signal is as shown in Ref. [5], as: $A_{\text{eff}}^{ps}(\omega_p, \omega_s) = [A_{\text{eff}}(\omega_p) + A_{\text{eff}}(\omega_s)]/2$.

We used this assumption of Gaussian spatial modes to re-scale each of the Raman gain coefficients curves from their original pump wavelengths to a new pump wavelength of 1454 nm. A_{eff} was calculated from the refractive index profile. Figure 2 shows the re-scaled coefficients versus the frequency difference between pump and signal, $(\omega_p - \omega_s)$.

Starting from the measurements made for pump wavelengths that span 73 nm, we obtain a prediction of the Raman gain coefficient for the new pump wavelength that differ by only 4%, confirming the validity of this approach.

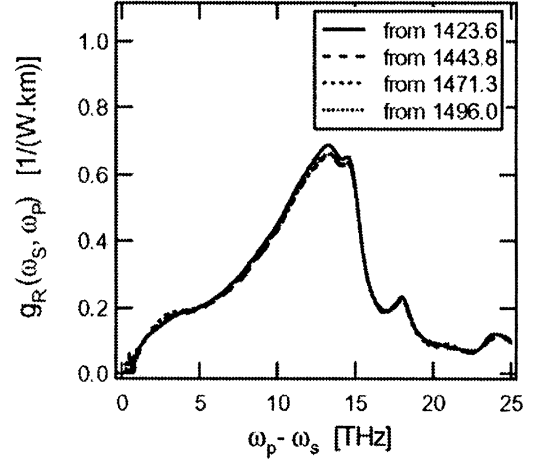


Fig. 2: Re-scaled Raman gain coefficients versus frequency difference between pump and signal for a 1454-nm pump.

This example also demonstrates that the reduction in Raman efficiency with increasing pump wavelength is due in part by the reduced spatial overlap between the pump and signal modes. The difference between the peak Raman gain coefficients for 1423.6 nm and 1496 nm pumps is approximately 15%, which can only be partially accounted for by the 5% reduction in ω_p . Hence, to fully explain the reduced Raman efficiency one must take into account the reduced overlap of pump and signal with increasing pump wavelength.

Conclusion

In this work we have demonstrated how the Raman gain coefficient scales with fiber design and pump wavelength, with emphasis on the scaling with effective area and pump wavelength. In one example, the Raman gain coefficient decreases 10%, when the pump wavelength increases 73 nm. It is demonstrated that a Raman gain coefficient measurement may be accurately scaled to other pump wavelengths if the refractive index profile of the fiber or the effective area versus wavelength is known.

References

- [1] G. Agrawal "Nonlinear Fiber Optics", Academic Press, 1995
- [2] P. N. Butcher and D. Cotter: "The Elements of Nonlinear Optics" Cambridge Studies in Modern Optic Vol. 9, Cambridge University Press 1990.
- [3] A. Yariv "Quantum Electronics", John Wiley and Sons, Third edition, 1989.
- [4] J. Bromage, K. Rottwitt, and M.E. Lines, IEEE PTL, vol. 14, p. 24 (2002)
- [5] W.P. Urquhart and P.J. Laybourn, IEE Proc., vol. 132, p. 201 (1985)